

THE FORMATION OF THE HUBBLE SEQUENCE

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Abstract The history of galaxy formation via star formation and stellar mass assembly rates is now known with some certainty, yet the connection between high redshift and low redshift galaxy populations is not yet clear. By identifying and studying individual massive galaxies at high-redshifts, $z > 1.5$, we can possibly uncover the physical effects driving galaxy formation. Using the structures of high- z galaxies, as imaged with the Hubble Space Telescope, we argue that it is now possible to directly study the progenitors of ellipticals and disks. We also briefly describe early results that suggest many massive galaxies are forming at $z > 2$ through major mergers.

Introduction

Astronomers have come a long way in the last decade towards detecting and studying galaxies out to redshifts $z \sim 6$. However, the principle goal of observational galaxy formation studies, understanding how high redshift and low redshift populations are connected, and thus *how* galaxies form, remains largely unknown. The traditional method of studying galaxy formation is to try and answer *when* galaxies formed, e.g., through star formation and stellar mass assembly histories and by detecting various galaxy populations such as extremely red objects, Lyman-alpha emitters, and Lyman-break galaxies. These galaxies, and their stellar populations, tell us when galaxies formed, but they do not, and empirically cannot, tell us how they formed.

An approach to this problem is to use ancillary information about galaxies not available from spectroscopy or integrated photometry. One method is to utilize structural information from high- z galaxies, imaged with HST, to determine when normal galaxies (hereafter defined as giant ellipticals and spirals) formed, as well as how. Techniques for doing this are now developed (Conselice 2003) and early results demonstrate that we can identify and trace the physical processes responsible for the formation of galaxies at $z > 1.5$. In this

article we briefly describe these approaches for understanding the formation of the Hubble sequence, or normal galaxies, and give some preliminary results.

Galaxies Near and Far

Bright and massive galaxies in the nearby universe are disks and ellipticals. At higher redshifts, the brightest galaxies in rest-frame UV selected samples nearly all have structural peculiarities (Conselice et al. 2003a). When did normal disks and ellipticals form? Figure 1a demonstrates through an $I < 27$ selected sample in the Hubble Deep Field North (HDF-N) that the high redshift galaxy population is dominated by peculiars, while at low- z ellipticals and spirals are common. This transition is robust to effects of resolution, noise, and morphological k-corrections (Conselice et al. 2004, in prep.)

A fundamental question to ask is whether these high redshift peculiars, often called Lyman-break galaxies (LBGs), transform into disks and ellipticals. LBGs are likely the progenitors of massive nearby systems, based on their clustering properties (Giavalisco et al. 1998). However, LBGs are observed to have low stellar masses, generally $< M^*$ (e.g., Papovich et al. 2001). If LBGs passively evolve, they will not contain enough mass to become massive, $> M^*$, galaxies at $z \sim 0$. If we can determine the future evolution of LBGs, and other high redshift galaxy populations, we can begin to piece together the history of galaxy formation.

The Galaxy Merger History

There are a few major methods by which galaxies can form. The first is an early collapse when stars form in rapid bursts which then passively evolve. Other methods are due to hierarchical accretion of intergalactic material, or mergers with other galaxies. The formation methods of galaxies are hard to trace, although based on the star formation history of the universe it is unlikely that most galaxies formed rapidly and early (e.g., Madau et al. 1998).

One method that can be traced is the incidence of major mergers. Major mergers in the nearby universe create distinct disturbed asymmetric morphologies that can be distinguished from pure star forming systems through the use of indices that measure asymmetries and the clumpiness of light distributions (Conselice et al. 2000; Bershadsky et al. 2000; Conselice 2003). The basic idea is that galaxies which are asymmetric, without a corresponding high degree of light clumpiness, are likely to be involved in major mergers (Conselice 2003). How well does the asymmetry index (A) identify known mergers? Figure 1b shows the deviation in sigma units between asymmetry (A) and clumpiness (S) values for nearby normal galaxies and major mergers. While normal galaxies have mostly low σ deviations from the A-S correlation, major mergers span a much larger range and include the most asymmetric objects.

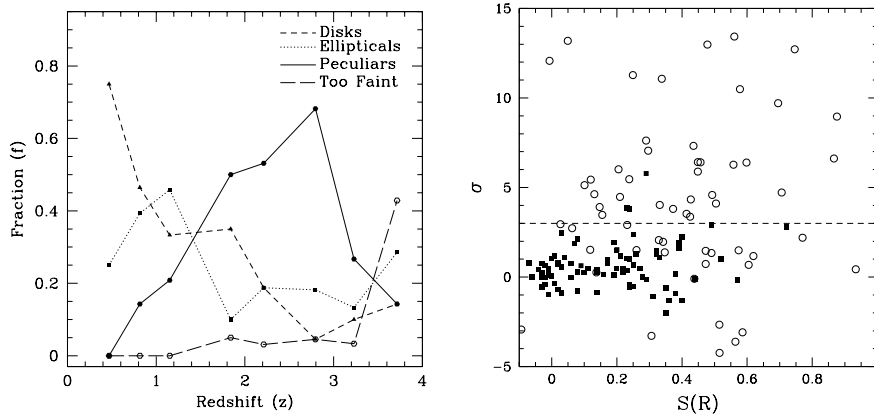


Figure 1. Left panel (a) - the morphological distribution as a function of type in the HDF, normalized to $I < 27$ counts. Right panel (b) - the sigma deviation from the asymmetry-clumpiness correlation, showing that major mergers (open circles) deviate by more than 3σ from this relationship, while normal galaxies (solid boxes) generally do not.

We can use asymmetry values of HDF-N galaxies to measure the evolution of implied major merger fractions out to $z \sim 3$. We avoid morphological K-corrections by using the rest-frame B-band asymmetries of galaxies in the HDF-N (Conselice et al. 2003a). We define major mergers as galaxies with rest-frame B-band asymmetry larger than $A_{\text{merger}} = 0.35$. By taking the ratio of galaxies with asymmetries $A > A_{\text{merger}}$ to the total number of galaxies in a given parameter range, implied merger fractions out to $z \sim 3$ can be computed as a function of absolute magnitude (M_B), stellar mass (M_*), and redshift (z). This allows us to determine how and when galaxies formed as a function of stellar mass and time.

Major merger fractions for galaxies brighter than $M_B = -21$ and -19 in the HDF-N are plotted in Figure 2a, along with semi-analytical model predictions of the same quantities. From this it appears that a large fraction of the brightest galaxies are undergoing mergers, while fainter systems generally do not. The fraction of bright galaxies undergoing major mergers drops quickly at lower redshifts, while the fainter systems have merger fractions that remain largely constant with redshift (Conselice et al. 2003a). Semi-analytic model predictions of the same quantities, based on Durham group simulations, do a relatively good job of predicting merger fractions at high redshift, but over predict the degree of major merging at lower redshifts for the most luminous and massive galaxies (Figure 2a).

Merger and Stellar Mass Accretion Rates

Using further information we can investigate the merger and stellar mass accretion rates of galaxies from $z = 0$ out to $z \sim 3$, or to when the universe

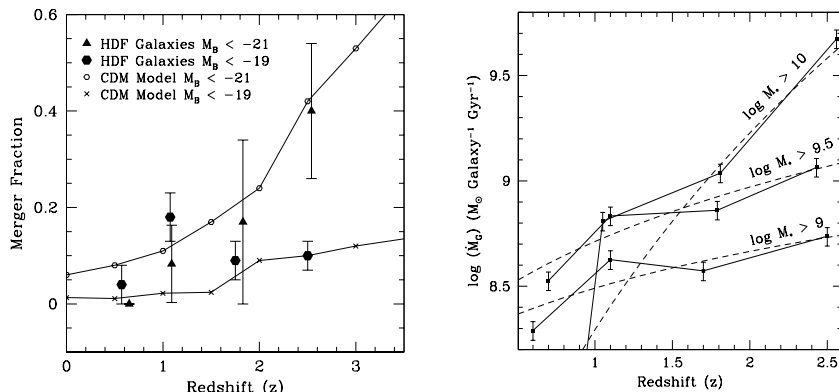


Figure 2. Left panel (a) - major merger fractions to $z \sim 3$ at magnitude limits $M_B = -21$ and -19 . Semi-analytical model predictions are also shown. Right panel (b) - stellar mass accretion history from major mergers as a function of initial mass (see Conselice et al. 2003a).

was only ~ 2 Gyr old. By assuming a merger time scale of 1 Gyr, and that each merger consists of two galaxies of equal mass, we can measure the rate of merging, and the stellar mass accretion rate due to major mergers. We can also determine how this accretion history varies with initial stellar mass (Figure 2b; Conselice et al. 2003a,b). Based on these empirical measurements, the amount of stellar mass added to a $M \sim 10^{10} M_\odot$ LBGs due to star formation and merging is enough to create a massive $> M^*$ galaxy at $z \sim 0$ (Conselice 2004, in prep).

Disk galaxies likely cannot form through these merger processes as they would not easily survive mergers at high redshift. These systems are therefore likely forming at about the same time they appear morphologically, at $z \sim 1.5$ (Figure 1). These galaxies have now possibly been identified at $z > 1.5$ by their low light concentrations in GOODS ACS images (Conselice et al. 2003c). These luminous diffuse objects (LDOs) are common at redshifts $1 < z < 2$ and have co-moving volumes similar to nearby massive disks. Follow up on these systems is now in progress.

References

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